Piezoresponse Force Microscopy (PFM) on GaN Nanowires

David Horton, UF

Collaborators: Dr. A Ural, J. Johnson – UF

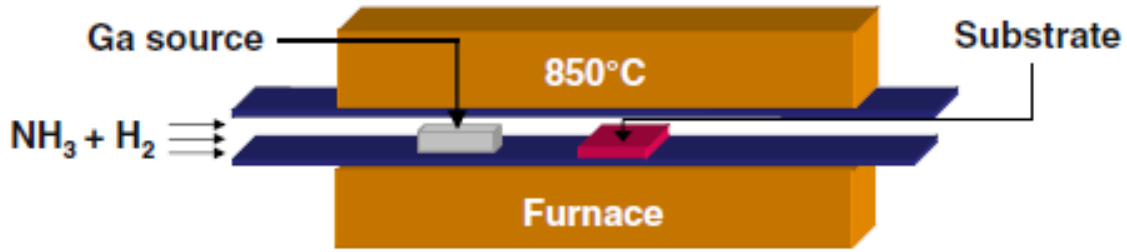
Dr. S Jesse, Dr. S Guo – Oakridge Natl. Lab

GATOR Engineering

UNIVERSITY OF FLORIDA

Growth of nanowires

- Grown by catalytic CVD using Au or Fe catalyst nanoparticles [1]

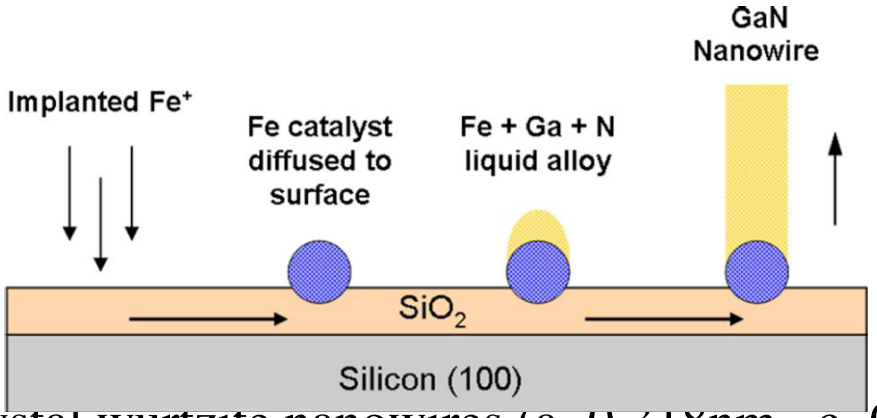


- NH_3 gas flow provides N via : $2Ga + 2NH3 \rightarrow 2GaN + 3H2$

- Growth time, growth temp, flow rate, flow composition and Ga source/ substrate distance influence growth

Growth of nanowires

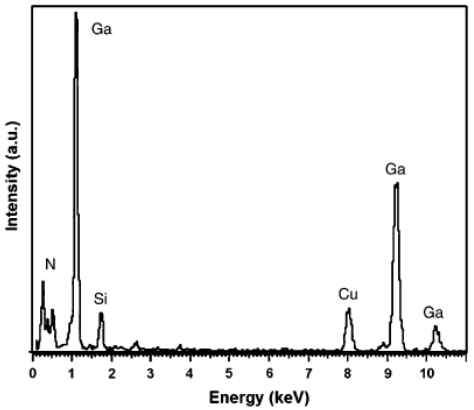
- Growth explained by VLS growth mechanism [2]
  - V: Ga, N from vapor adsorb on nanoparticle surface
  - L: Ga, N and Metal liquid alloy forms around initial particle
  - S : Ga, N attain solubility limit and precipitate solid GaN out of solution



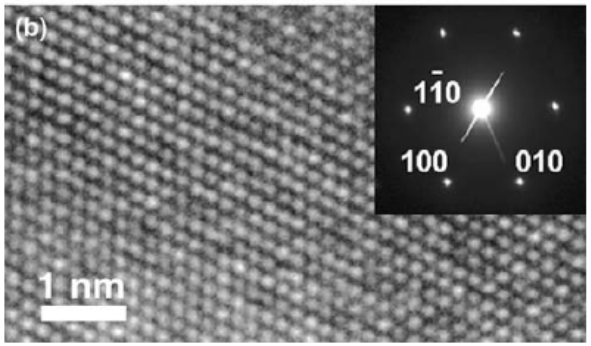
- Single crystal wurtzite nanowires (a=0.318nm , c=0.517nm)

Characterization of nanowires

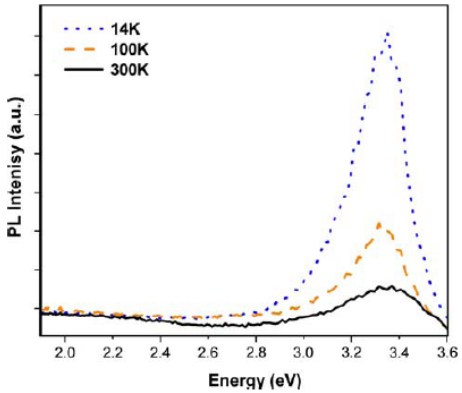
EDS Spectrum [1]:



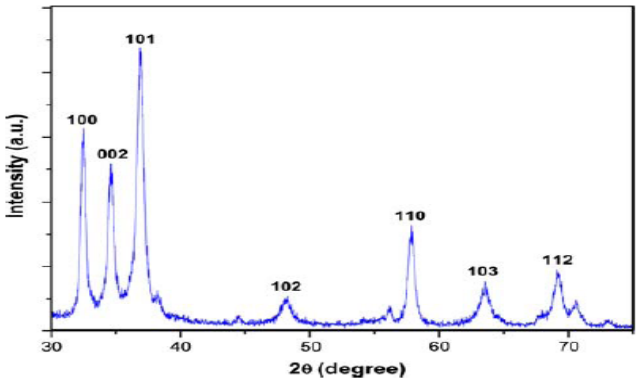
HRTEM [1]:



PL Spectrum [1]:

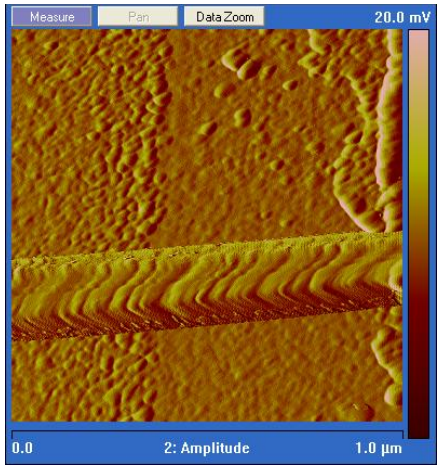


XRD Spectrum [1]:

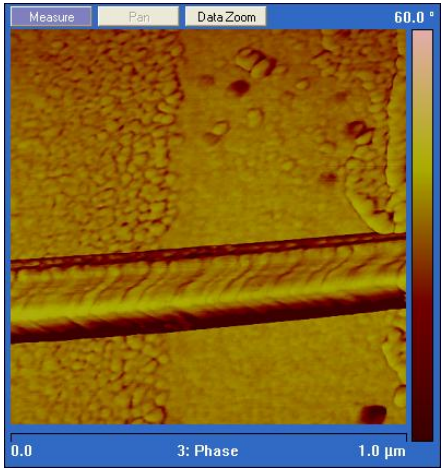


AFM Characterization

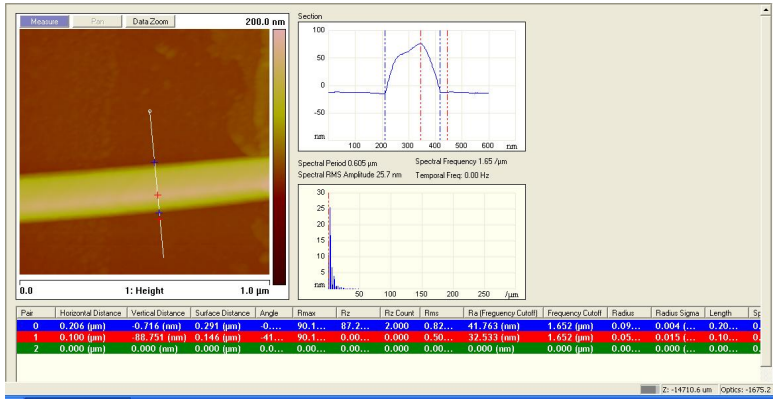
a)



b)



c)



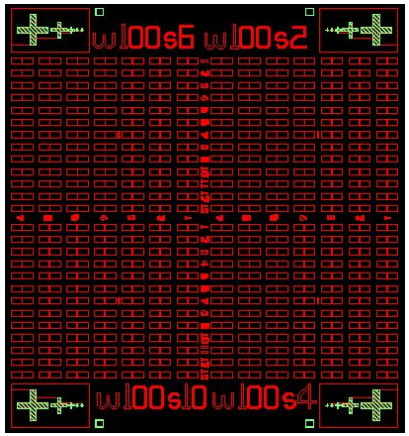
a) Amplitude

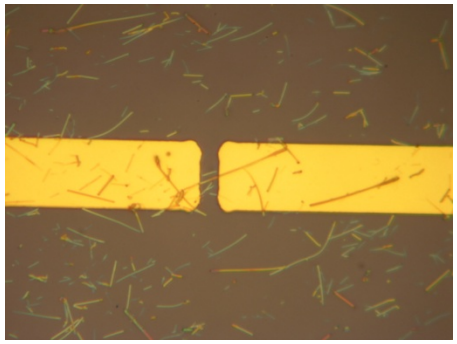
b) Phase

c) Width~200nm,

Deposition of nanowires on contact grid

- As-grown nanowires dispersed in 2-propanol and sonicated. Suspension deposited on contact grid.

a) 

b) 

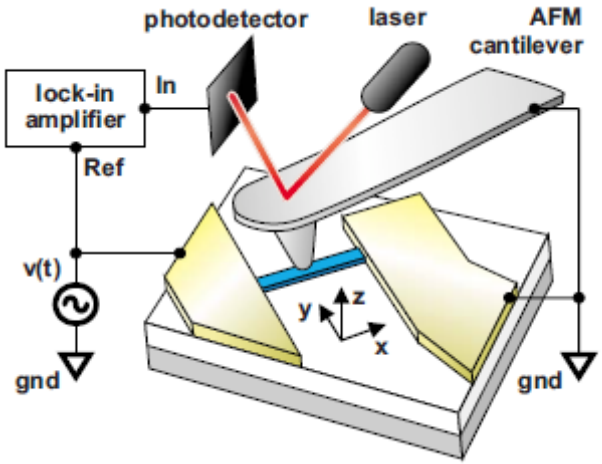
a) Contact grid

b) Optical bright field image of nanowires

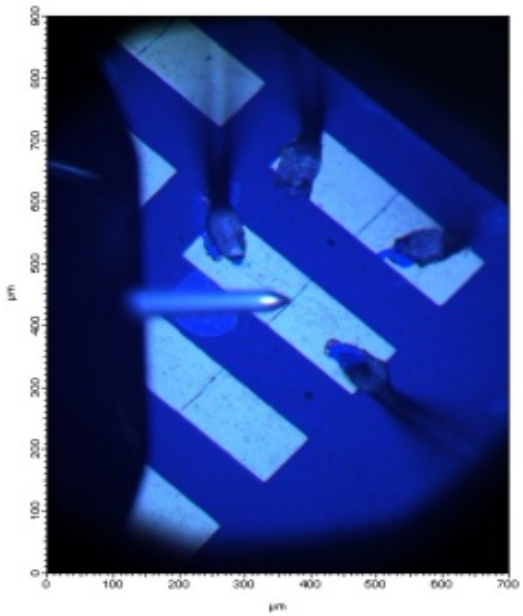
- Ti/Al/Pt/Au contact electrodes patterned by photolithography, e-beam evaporation and subsequent lift-off.

Experimental Set up and Method

- PFM on
  - Unconnected (freestanding) wires
  - Connected wires



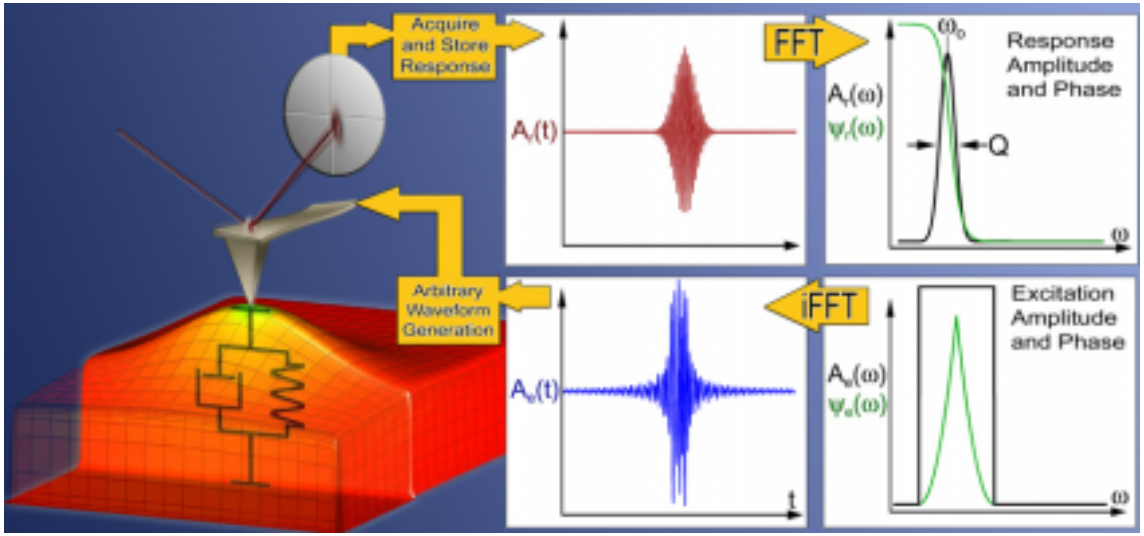
a) PFM setup [3]



b) Image of wire-bonded contacts and tip used during experiment

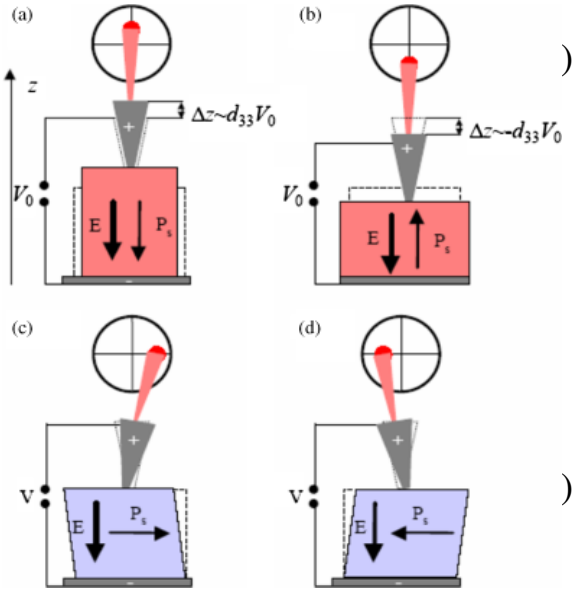
Experimental Set up and Method

- Frequency Band Excitation Method [4]
  - Simultaneous excitation and detection within a band of frequencies rather than at a single frequency
  - Only selected regions of Fourier space contain information of interest
  - Method yields full frequency response at each measured point



Piezoresponse investigated by PFM (experimental)

- Relationship (reduced to linear) between electric field, E and mechanical strain, ε: $\varepsilon_i = d_{ij} E_j$ where j=1…3 and i=1….6



) tensile, compressive normal strains d_{33}

) shear strains d_{15}

- Single crystal GaN nanowire polarization along [0001] direction (figures **c** and **d**) [5]. Back to slide 10

Piezoresopnse investigated using FLOOPS (simulation)

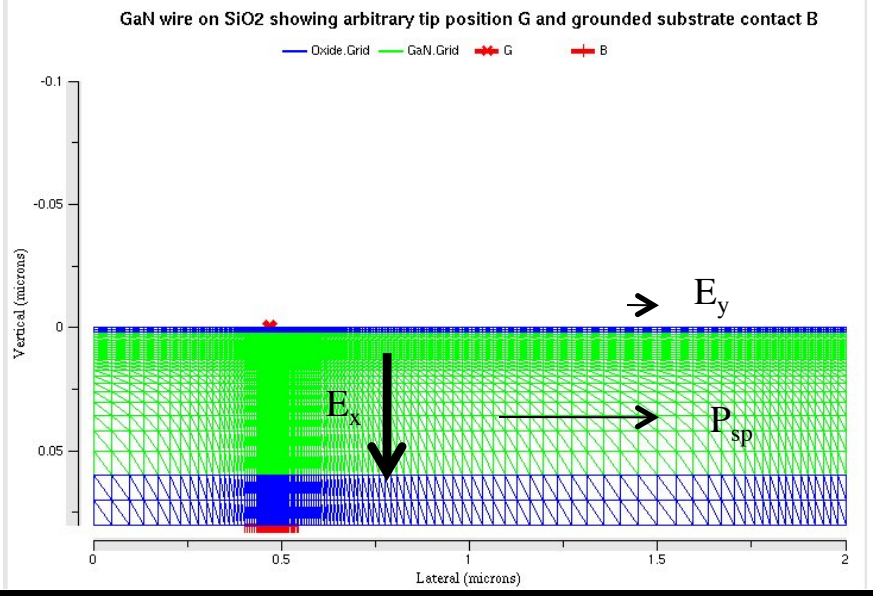
- Assuming axes in 2D as: E_y E_x
- Nanowire and polarization , P_{sp} in [0001] parallel to y axis while lying flat. Applied field from tip, E_x is to P_{sp} Refer to: Slide 9 figs.c & d. E_y is to P_{sp}
- Normal deformation comes from the piezoresponse of small volume just underneath the tip
- Assuming constant d_{33}, d_{13}, d_{15} in vicinity of tip, resultant measured strain in volume given by :

$$\varepsilon(x) = d_{15} \int E_x(x,y)\, dx + d_{13} \int E_y(x,y)\, dy$$

d_{15} =3.1pm/V , d_{15} =-1.7pm/V [6]

Piezoresponse investigated using FLOOPS (simulated)

- Unconnected GaN nanowire set up:
  - Wire Thickness = 60nm
  - Surface oxide thickness = 2nm
  - SiO2 thickness (which wire is resting on) = 20nm
  - Grounded substrate



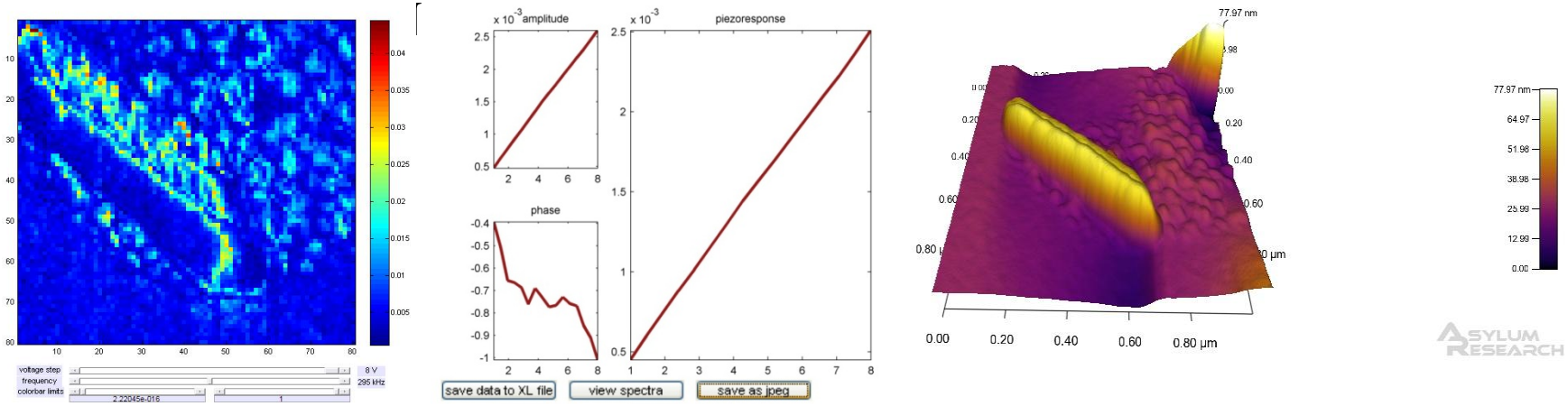
Using coefficient matrix:

$$\begin{pmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{xy} \end{pmatrix} = \begin{pmatrix} 0 & d_{31} \\ 0 & d_{33} \\ d_{15} & 0 \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

Measured strain = $\varepsilon_{xx} + \varepsilon_{xy}$

*E_x large, E_y small

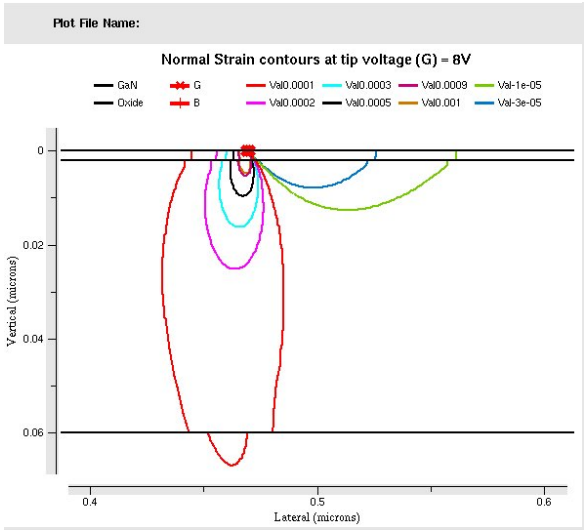
Experimental results: Piezoresponse of Unconnected GaN nanowire

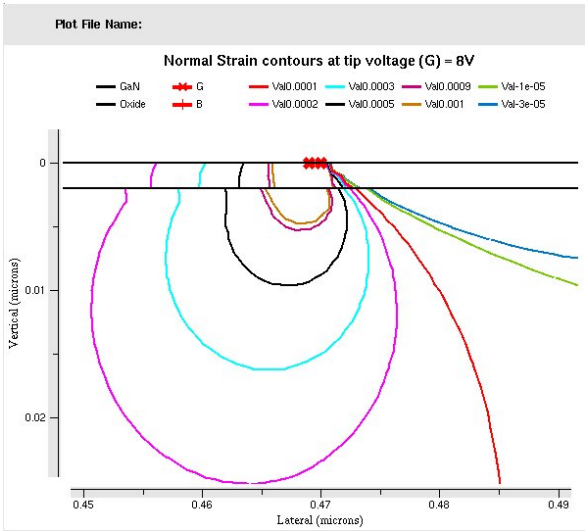


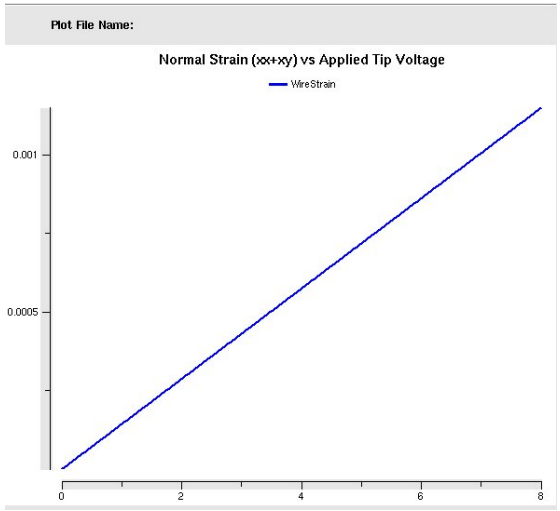
a) Piezoresponse at 8V b) Hysteresis curves c) 3D image of wire

- Linear piezoresponse from $1 \leq V \leq 8$ tip voltage

Simulation results : Piezoresponse of Unconnected GaN nanowire

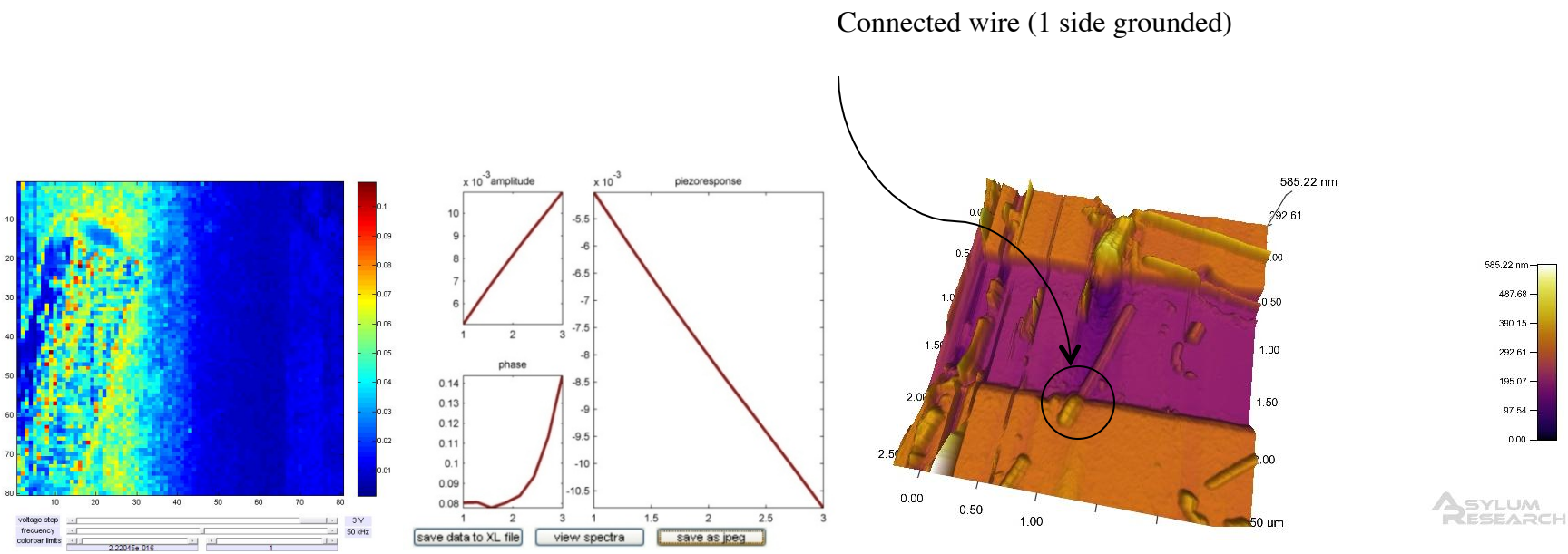






- Wire strain on curve determined by taking an average strain (xx+xy) *of 7 points in a 4nmx 4nm area directly underneath tip contact
- * No clamping effect for free standing wire,

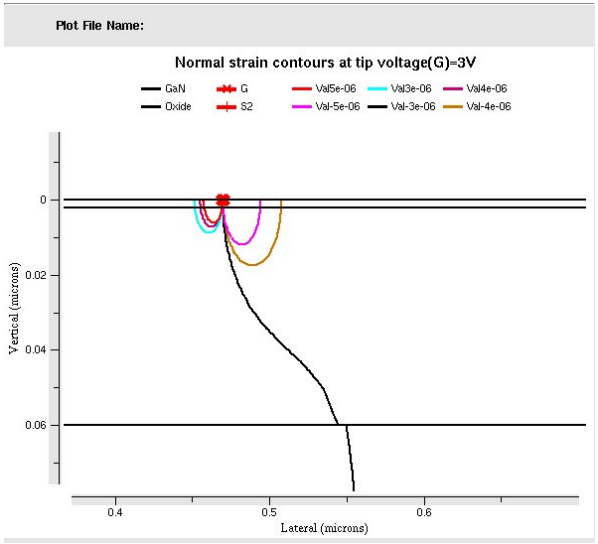
Experimental results: Piezoresponse of Connected GaN nanowire

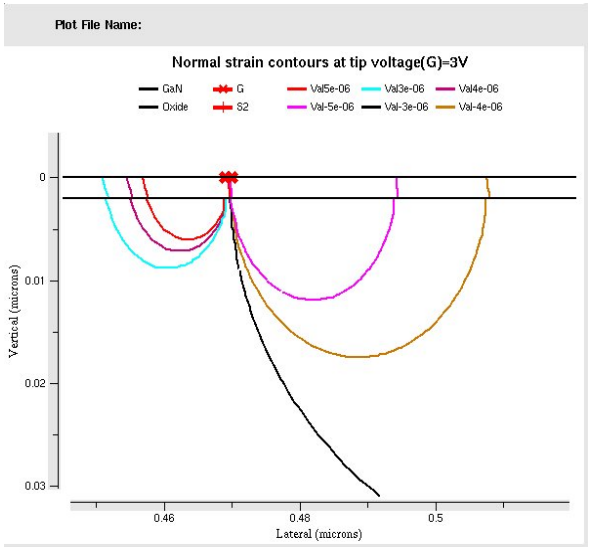


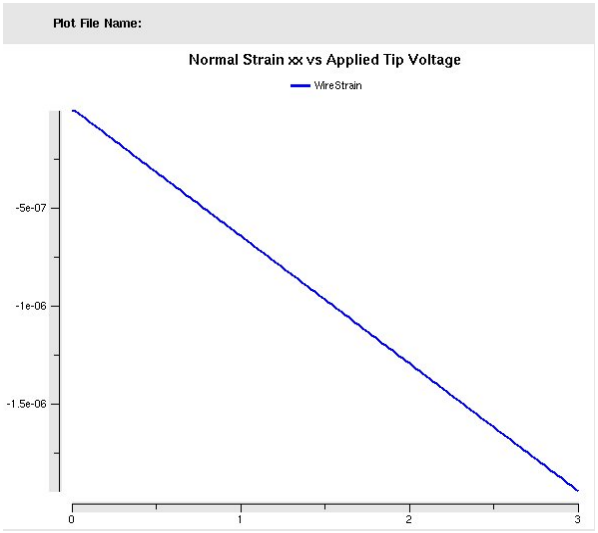
a) Piezoresponse at 3V b) Hysteresis curves c) 3D image of wire

- Linear piezoresponse from 1≤ V≤ 3 tip voltage

Simulation results : Piezoresponse of Connected GaN nanowire

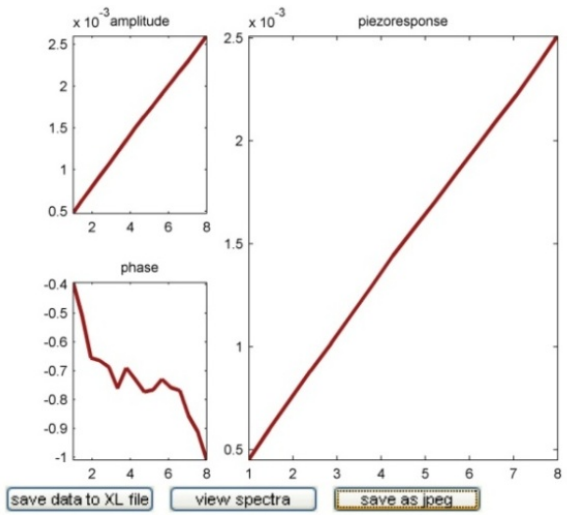


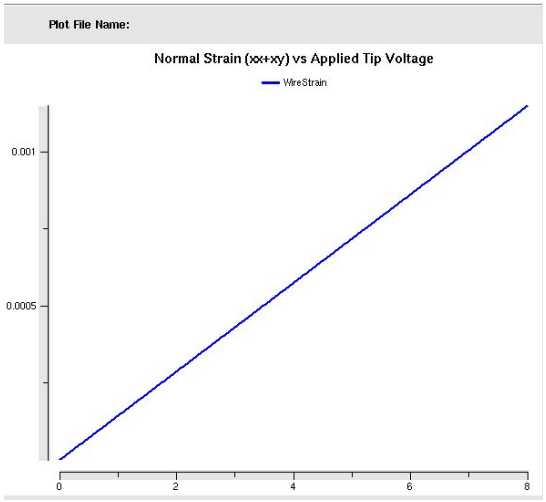


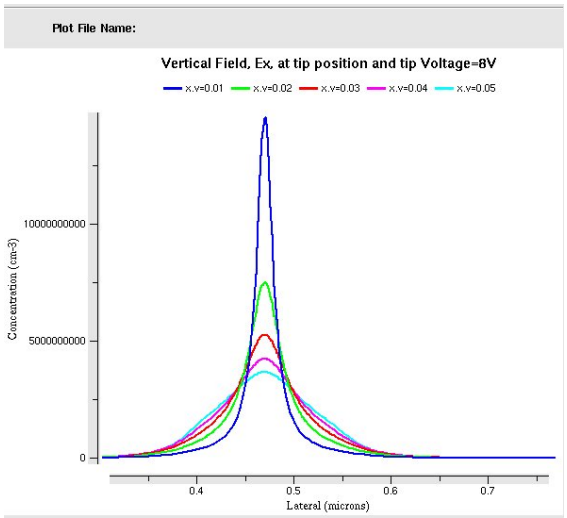


- Wire strain on curve determined by taking an average strain (xx)* of 7 points in a 4nmx 4nm area directly underneath tip contact
- * Contact restricts shearing forces, so xy component is removed due to clamping effect

Experimental vs Simulated comparison for Unconnected GaN nanowire

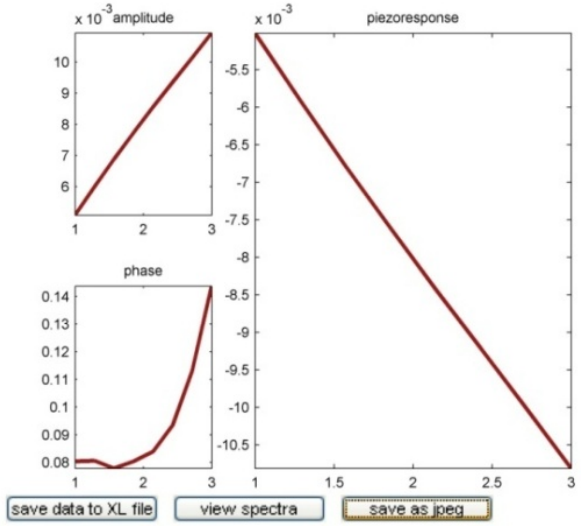


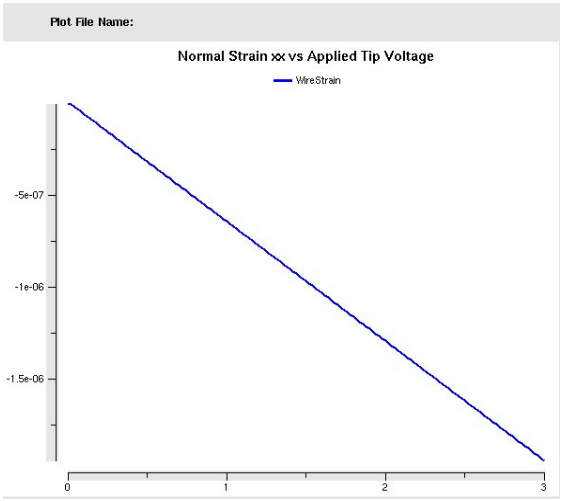


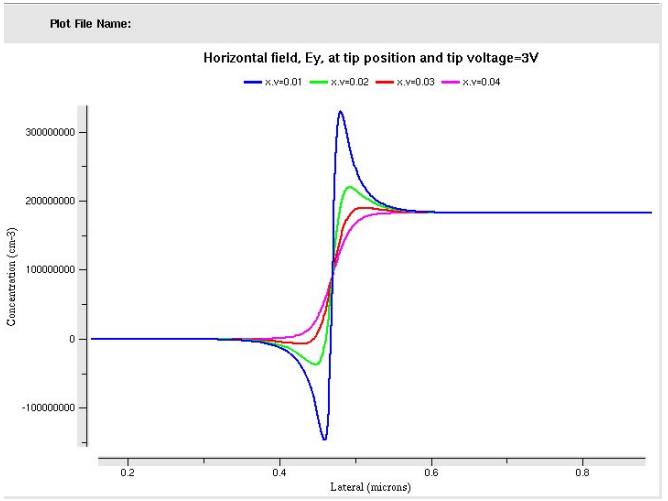


- Experimental and Simulated piezoresponse at 8V are 2.5e-3 and 1.14e-3 respectively. Decent agreement between the two.
- For unconnected wire, E_x dominates, E_y is negligible so **Shear** strain, $\mathbf{d_{15}}$ dominates the measured response.

Experimental vs Simulated comparison for Connected (1 side) GaN nanowire







- Experimental and simulated piezoresponses show same trend. Clamping (displacement=0 at edge) causes shear strain contribution from E_x to be minimized.
- For connected wire, E_y determines strain. Coeff. $\mathbf{d_{13}}$ (Poisson's ratio) determines the measured response.

Conclusions and Further Work

- Initial 2D strain simulations using coefficients listed for bulk GaN in reasonable agreement with nanowire piezoresponse measured by experiments.
- 3D simulation needed for more accurate comparison.
- Measurement on fully connected (2 sides) GaN nanowires
- Simulation of experimentally measured hysteresis effect.
- Extraction of accurate coefficients specific to GaN nanowires difficult due field superposition and inevitable clamping effect

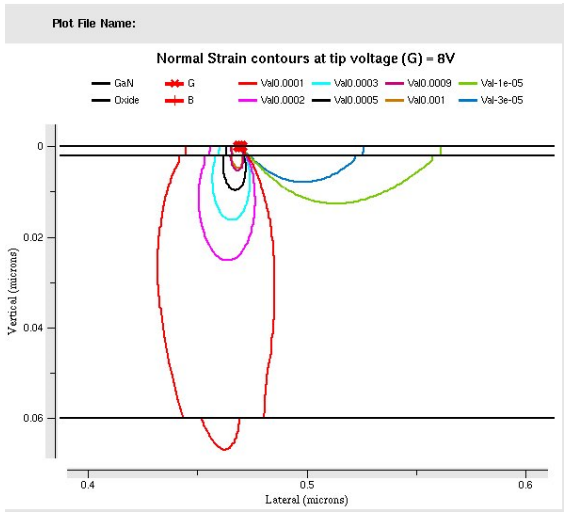
References

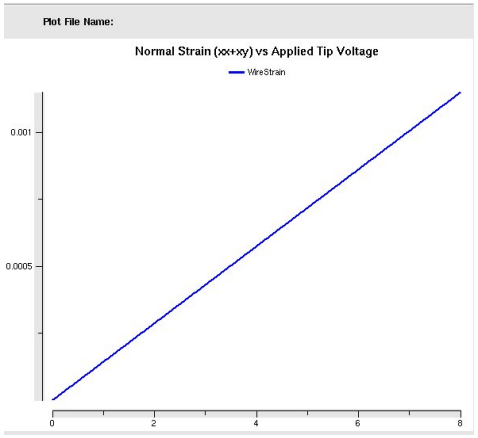
- 1] Jason L. Johnson, Yongho Choi, Ant Ural , Wantae Lim, J.S. Wright, B.P. Gila, F. Ren and S.J. Pearton: *Growth and Characterization of GaN Nanowires for Hydrogen Sensors* ,J. of Elec. Materials. Vol 38, No. 4, 2008
- 2] Jason L. Johnson, Yongho Choi, and Ant Ural: *GaN nanowire and Ga_2O_3 nanowire and nanoribbon growth from ion implanted iron catalyst* ,J. Vac. Sci. Technol. B Vol 26, No.6, 2008
- 3] J. Wang, C. Stampfer, C. Roman, W. H. Ma, N. Setter,C. Hierold: *Piezoresponse force microscopy on doubly clamped KNbO3 nanowires* , Applied Phys. Lett. Vol 93, No 223101, 2008
- 4] Stephen Jesse, Sergei V Kalinin, Roger Proksch, A P Baddorf, B J Rodriguez: *The band excitation method in scanning probe microscopy for rapid mapping of energy dissipation on the nanoscale*, Nanotechnology Vol 18, 2007
- 5] Nina Balke, Igor Bdikin, Sergei V. Kalinin, Andrei L. Kholkin: *Electromechanical Imaging and Spectroscopy of Ferroelectric and Piezoelectric Materials: State of the Art and Prospects for the Future*, J. Am. Ceram. Soc., Vol 92, No.8, 2009

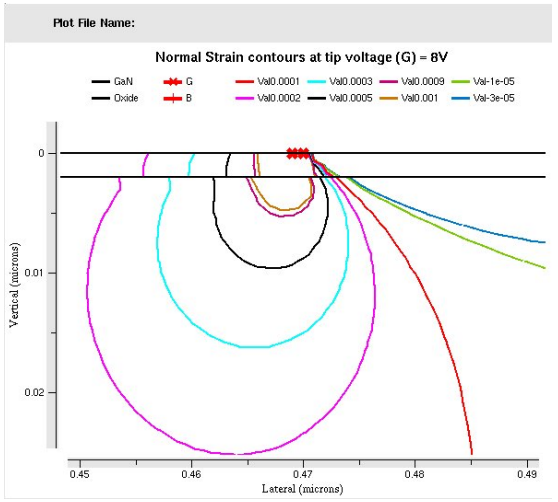
Back-up Slides

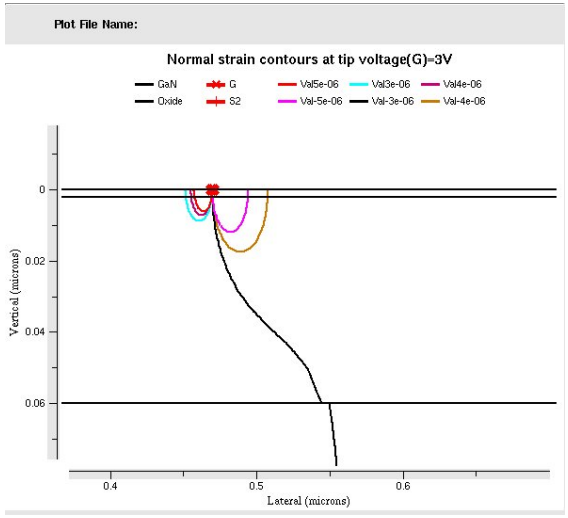
- Slide 21 - Simulation pictures
- Slide 22 – Experiment results showing hysteresis

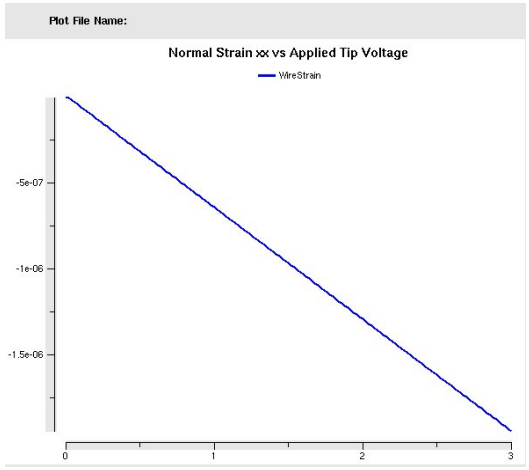
Unconnected and connected wire simulation pictures

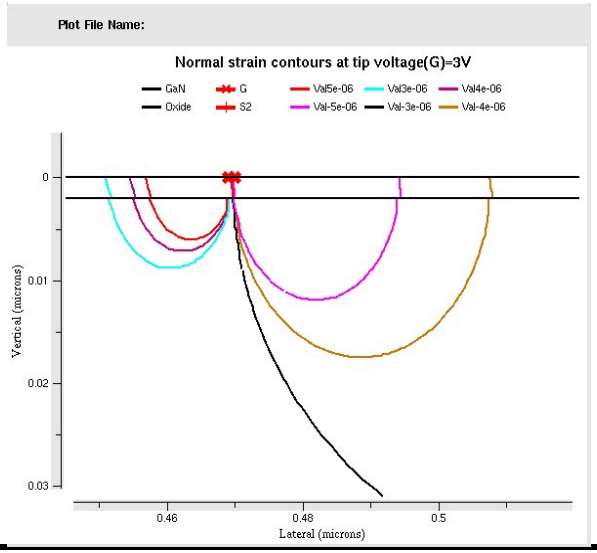






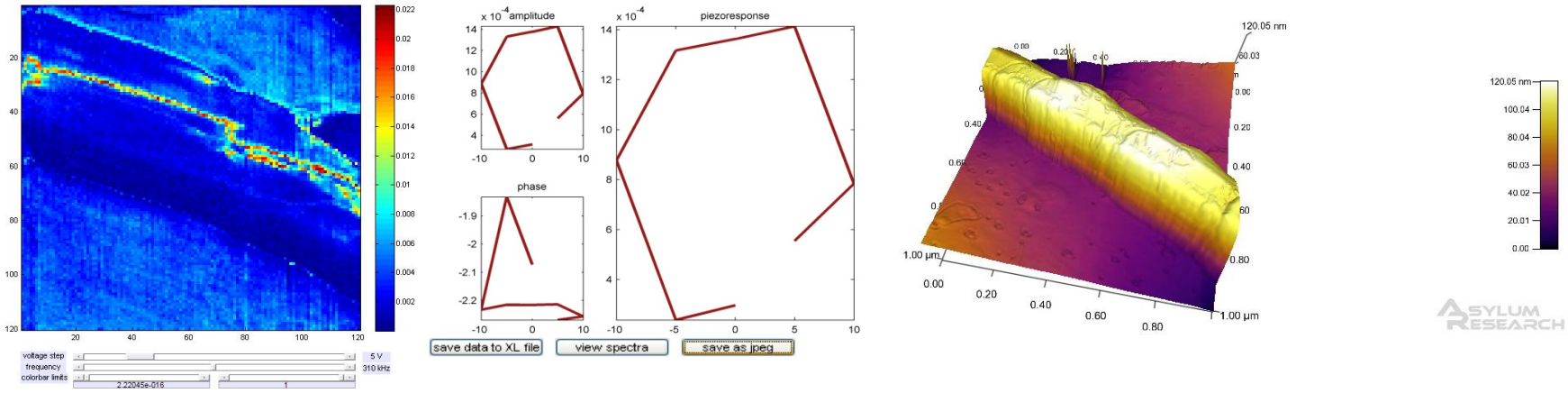






Experimental results: Piezoresponse with Hysteresis

- Unconnected GaN nanowire



a) Piezoresponse at 5V b) Hystersis curves c) 3D image of wire

- Hysteresis from ↑ ↑ ↑. ↓ ↓ ↓ . $+5 \leq V \leq 0$ tip voltage swing